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Top physics at LHC: From cross-section measurements to new physics searches

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Summary. — This paper is an overview of recent results on top-quark physics, obtained by the ATLAS and CMS Collaborations, from the analysis of pp collisions at $\sqrt{s} = 8$ and 13 TeV at the Large Hadron Collider. Total and differential top-quark pair and single top cross-sections are presented together with new physics searches involving top quarks.

1. – Introduction

The top quark is by far the heaviest of all known quarks, approximately 40 times heavier than its partner, the bottom quark. Once the bottom quark was experimentally discovered in 1977, the existence of a charge-2/3 quark in the third quark generation was expected to preserve the Standard Model (SM).

The top quark was discovered at Fermilab by both the CDF [1] and DØ [2] Collaborations in 1995 at the Tevatron collider.

The top quark is special not only due to its large mass, but also due to its short lifetime which prevents it from hadronizing before decaying, *i.e.* there are no bound state hadrons made of top quarks. This allows to experimentally test the properties of the bare top quark itself without diluting information in the hadronization process.

At hadron colliders, top quarks are produced either in pairs, dominantly through the strong interaction, or singly through the weak interaction. Thus, top quark production and decay allow to test the features of two fundamental forces described by the SM.

Besides its potential role in electroweak symmetry breaking, the top quark plays an important role in many scenarios for new physics beyond the SM (BSM). Several models predict the existence of new particles which decay predominantly into top-quark pairs. Therefore, it is attractive to search for resonances in the top-quark pair invariant-mass distribution.

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This overview will describe some of the recent measurements of top-pair and single-top production cross-section and of BSM searches involving top quarks, covering only a selection of the top physics results achieved by the ATLAS and CMS Collaborations using data collected in 2012 at $\sqrt{s} = 8\,\text{TeV}$ and in 2015 at $\sqrt{s} = 13\,\text{TeV}$.

An updated and more complete list is available at the ATLAS ([1]) and CMS ([2]) public top results website. The ATLAS and CMS detectors are described in [3] and [4] respectively.

2. – Inclusive cross-section of top-quark pair

The top-antitop quark production cross-section $\sigma_{t\bar{t}}$ in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ has been measured by the ATLAS [5] and CMS [6] detectors at LHC in the final state with oppositely charged $e\mu$ pair. The measurement was performed with the dataset taken in 2015 corresponding to an integrated luminosity of $3.2\,\text{fb}^{-1}$ for ATLAS, and $2.2\,\text{fb}^{-1}$ for CMS.

In ATLAS the number of events with exactly one and exactly two b-tagged jets were counted and used to simultaneously determine $\sigma_{t\bar{t}}$ and the efficiency to recostruct and b-tag a jet from a top quark decay, thereby minimising the associated systematic uncertainties.

CMS performed the analysis by considering events with one electron and one muon and at least two jets, one of which is required to be identified as a b-jet.

The total cross-sections measured by the two experiments ATLAS (1) and CMS (2) are respectively:

$$\sigma_{t\bar{t}} = 803 \pm 7(stat) \pm 27(syst) \pm 45(lumi) \pm 12(beam)\,\text{pb}, \tag{1}$$

$$\sigma_{t\bar{t}} = 793 \pm 8(stat) \pm 38(syst) \pm 21(lumi)\,\text{pb}. \tag{2}$$

where uncertainties arise from data statistics, systematic uncertainties, knowledge of the integrated luminosity and ATLAS quoted also the one related to LHC beam energy. The results are consistent with the theoretical QCD calculations at the NNLO [7]:

$$\sigma^{th}_{t\bar{t}}\,(13\,\text{TeV}) = 832^{+40}_{-46}\,\text{pb}. \tag{3}$$

3. – Top-quark pair differential cross-sections

Thanks to the large integrated luminosity delivered by the LHC, more detailed measurements like differential cross-sections as a function of $t\bar{t}$ system kinematic variables are possible.

To reconstruct the kinematic of the $t\bar{t}$ events, two topologies are usually considered: *resolved* topology, for top quarks with low-p_T, where the top-quark decay products are well isolated and can be reconstructed individually; *boosted* topology, for high-p_T top quarks, where the top decay products are not well isolated and can be reconstructed as a single large-R jet.

([1]) `https://twiki.cern.ch/twiki/bin/view AtlasPublic/TopPublicResults.`
([2]) `http://cms-results.web.cern.ch/cms-results/public-results/publications/TOP/index.html.`

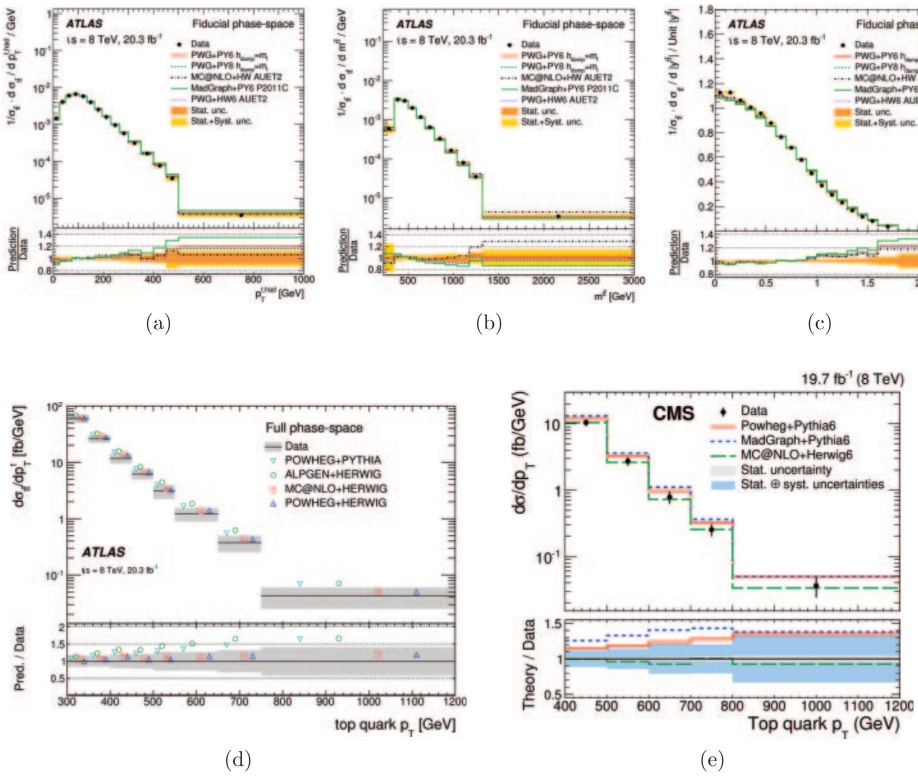


Fig. 1. – Top: differential $t\bar{t}$ cross-section at $\sqrt{s} = 8\,\text{TeV}$ as a function of the transverse momentum of the top quark (a); mass (b) and absolute rapidity (c) of the $t\bar{t}$ system measured by ATLAS using the resolved approach. Bottom: differential $t\bar{t}$ cross-section at $\sqrt{s} = 8\,\text{TeV}$ as a function of the transverse momentum of the top in the full phase space for highly boosted top quarks obtained by ATLAS (d) and CMS (e).

Both ATLAS and CMS experiments have measured at 8 TeV the $t\bar{t}$ fiducial differential cross-sections as a function of mass, transverse momentum, absolute rapidity of the system using the resolved approach [8, 9] and as a function of the top-quark transverse momentum using the boosted approach [10, 11].

The analyses have been performed using a cut-based approach in the lepton+jets channel. Once the reconstructed kinematic distributions are extracted, the cross-section is calculated in the fiducial and full phase space at the parton level via unfolding methods. The measurements have been compared to NLO predictions from Monte Carlo generators. In general, all measurements show good agreement with the theory, as shown in fig. 1, although both experiments have observed a trend where the theory overestimates the data at high p_T.

4. – Single top-quark production

At LHC a single top quark can be produced via electroweak interaction involving the Wtb vertex. Production measurements can be used to determine $|V_{tb}|$ and test the unitarity of the Cabibbo-Kobayashi-Maskawa matrix.

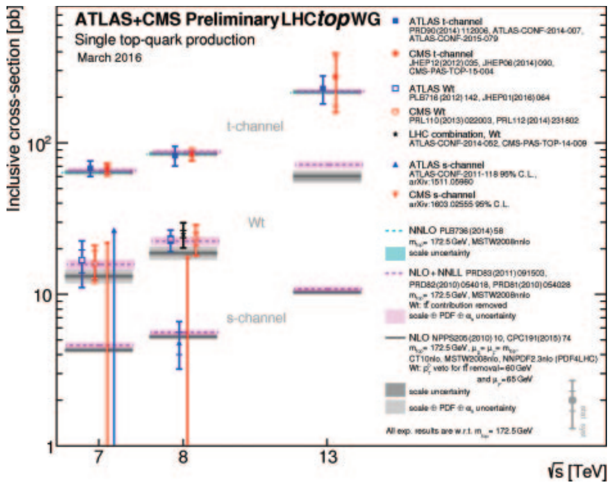
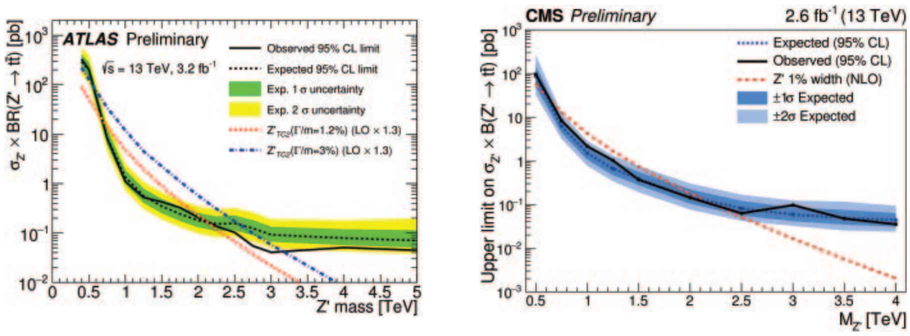


Fig. 2. – ATLAS and CMS measurements of the single-top production cross-sections in various channels as a function of the center of mass energy.

At $\sqrt{s} = 13\,\text{TeV}$ and $\sqrt{s} = 8\,\text{TeV}$ the single top-quark production inclusive cross-section has been measured by the ATLAS and CMS Collaborations in the t-channel and Wt-channel production mechanisms using the lepton+jets decay topology [12-15]. The first evidence at LHC for the s-channel production has been measured at 8 TeV by ATLAS in [16] while CMS limits are reported in [17].

Both experiments used a multivariate analysis (MVA) approach to perform the measurements. To separate single top-quark signal events from the expected background, several kinematic variables have been combined into one discriminant by employing a neural network (NN) or a boosted decision tree (BDT). Finally, the cross-section is extracted performing a simultaneous fit to the signal and background regions. Figure 2 shows the measured cross-section in agreement with the NNLO or NLO+NLL SM predictions.



(a) (b)

Fig. 3. – The observed and expected cross-section 95% CL upper limits on the Z'_{TC2} signal obtained by ATLAS (a) and 95% CL upper limits on the production cross-section times branching ratio for a Z' boson with relative width (Γ/M) of 1% decaying to $t\bar{t}$ obtained by CMS (b).

5. – New physics searches with top

Both ATLAS and CMS performed analysis [18, 19] at a centre-of-mass energy of 13 TeV in the lepton plus jets channel using a selection optimized for large resonance masses decaying to $t\bar{t}$, where the emerging top quarks have large Lorentz boosts. The invariant-mass spectrum of the candidate top-quark pairs is searched for excesses above the background expectation and used to set exclusion limits on the production cross-section times branching ratio for hypothetical $Z^{'}$ bosons, since no significant deviations from the Standard Model predictions are found, as shown in fig. 3.

6. – Conclusions

Total and differential top-quark pair and single-top cross-sections have been measured by the ATLAS and CMS experiments in pp collisions at $\sqrt{s} = 8$ and 13 TeV at LHC. No significant deviations from the SM predictions have been observed.

ATLAS and CMS performed also searches for high-mass resonance particles decaying in $t\bar{t}$ and 95% CL upper limits on the production cross-section times branching ratio for hypothetical $Z^{'}$ bosons have been derived.

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